much slower subsidence rate, because initiation of subsidence was delayed in that area. The top "Repetto" horizon downlaps onto it, and farther south, aggradation did not commence until after 2.5 Ma. Therefore, even though total subsidence is much greater beneath Hueneme Fan than south of Point Dume, subsidence rates may be similar. Early Pliocene "Repetto" strata are present offshore Venice Beach (see also Wright, 1991), and long-term average subsidence rates in that area are half those at Hueneme Fan.

## DISCUSSION

### Folds and the Fault Slips that Create Them

The Shelf Projection anticlinorium had previously been interpreted as en-echelon with, and distinct from, the Palos Verdes anticlinorium (Nardin and Henyey, 1978; Legg et al., in press). We remapped these anticlinoria and show that they are now a single structure, although with a slight local bend or right step in the axis (**Fig. 1**). We did not study the broad shelf south and southeast of Palos Verdes Hills; it is possible, perhaps likely, that the anticlinorium continues to the southeast. The studied 40+ km-long section of the anticlinorium, on both Palos Verdes Peninsula and at the Shelf Projection, include short-wavelength (1/2-1 km) folds. (**Fig. 10**; Dibblee, 1999; Fisher et al., 2003;). It is these folds that are en-echelon. The rocks involved in the short-wavelength folding are late Miocene (e.g., Nardin and Henyey, 1978), and we hypothesize that this short-wavelength folding occurred during (early?) Pliocene time and predates the larger structure. This folding succession may be common, as dated strata show that

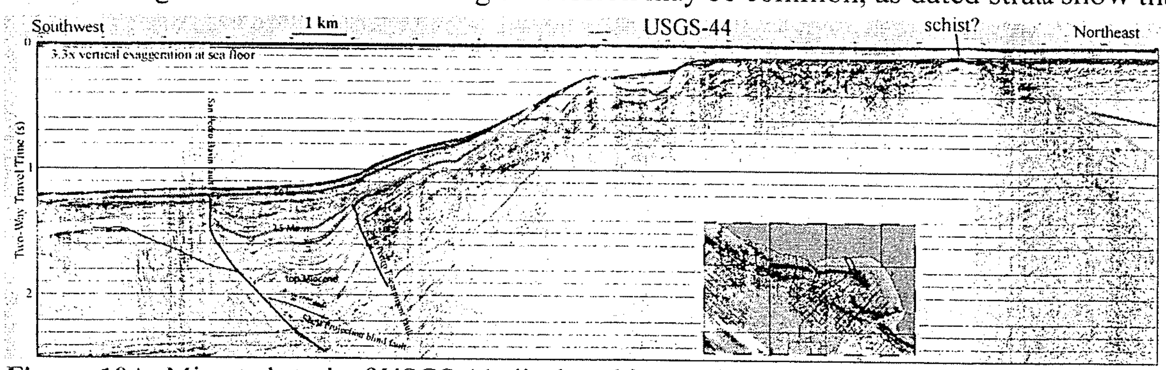


**Figure 10A:** Migrated stack of USGS 44, displayed in travel time, located as red line in inset and on Fig. 3A. Low-angle NE-dipping fault is the same as the one shown in Fig. 6. The San Pedro Basin fault likely offsets the low-angle fault. The part to the northeast was mapped as the Shelf Projection blind fault. Post-50 ka strata, above dark green, can be traced up the fold limb, and may be kinked above the tip of the San Pedro Escarpment fault. Top "Repetto" is brown; top Miocene is light green.

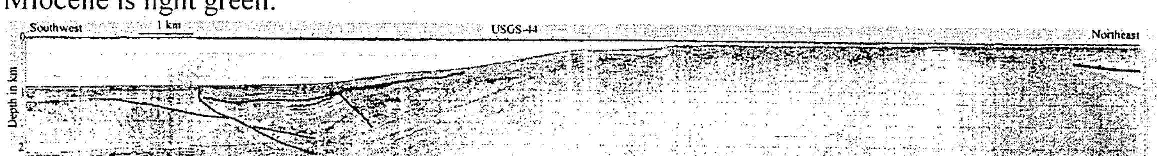


**Figure 10B:** Migrated stack of USGS 44, displayed in depth with no vertical exaggeration. This depth section was used for the top "Repetto" (brown) area balance shown in Figure 11A, B.

short-wavelength Pliocene folds precede long wavelength folding of the Channel Islands anticlinorium (Seeber and Sorlien, 2000).

Folds, in the absence of diapirism, are the product of slip on faults. If contraction is being actively absorbed in an anticline, then there must be a fault or ductile shear zone at depth that is slipping. Broad fold limbs along the California margin have generally been described as backlimbs above ramps in faults, whether the fault ramp is planar above a kink, or curved in cross section (listric) (Davis and Namson, 1994a,b; Shaw and Suppe, 1994, 1996; Seeber and Sorlien, 2000). Where a broad, long anticlinorium has two limbs, one might expect one limb to be a forelimb, and the other to be a backlimb. The forelimb can be due to slip dying out (e.g., Wickham, 1995), or due to flattening of a fault at the top of a ramp (e.g., Suppe, 1983), or to both. However, in the cases of the Northern Channel Islands anticlinorium and also Palos Verdes anticlinorium, both fold limbs have been interpreted as backlimbs. The north or northeast limb has been explained as a backlimb above the fault that forms the base of a tectonic wedge, and the south or southwest limb has been explained as a second backlimb above a backthrust that forms the roof of the thrust wedge (Davis et al, 1989; Shaw and Suppe, 1994, 1996). However, in both areas faults are imaged that dip north and northeast respectively beneath the south and southwest-dipping fold limbs (**Figs. 4, 6, 10**, Sorlien et al., 2000). We prefer to interpret these fold limbs as forelimbs, and present a model for formation of broad forelimbs.

Many examples and publications include forelimbs that are narrower and more steeply dipping than the backlimb (Suppe, 1983; Suppe and Medwedeff, 1990). However, broad forelimbs can form independently of a backlimb. If the deep part of a planar fault is slipping, and the shallow part is not, a forelimb of an anticline will form (e.g., Sibson, 1985). If the fault is very broad and gently dipping, and the slip is absorbed gradually up the dip of the fault, the fold limb may be broad and gently dipping. A class of forelimbs has been quantified as trishear folds (Erslev, 1991; Hardy and Ford, 1997; Allmendinger and Shaw, 2000). They can explain progressively-tilting forelimbs, and involve a triangular shear zone above the tip of a propagating blind thrust. Line lengths and volumes need not be preserved, as material can be transferred between the hanging-wall and footwall sides or vice-versa of a shear zone as it propagates through the material. While we are investigating application of a trishear model to the Palos Verdes-Shelf Projection anticlinorium, here we will use a simple graphical approach and simple area balancing in cross section to estimate slip on the blind faults. In **Figure 11C-D**, we show a model where a gently-dipping, progressively tilting forelimb is created to absorb slip.

**Slip Estimates**

**Figure 11A** and **11B** shows two end-member area balances of the anticlinorium using the depth section of USGS-44 (**Fig. 10B**). The area balance is based on folding since the time of deposition of the top "Repetto", at approximately 2.5 Ma. Post-"Repetto" slip is modeled between 0.8 km or 1.7 km, depending on choice of fault dip and initial stratal dip. Area balance is a simple technique, where one calculates the excess area above an originally flat surface or regional dipping surface (Woodward et al., 1989; Epard and Groshong, 1993). This is usually done on a fold where the fault flattens into a regional decollement/detachment, and it is necessary to estimate the depth to that detachment. The slip is estimated by constructing a rectangle of equivalent area to that in the fold, with the base of the rectangle being at the depth to detachment, and its width being fault slip. Here, we do not use the depth to detachment, which might be at the

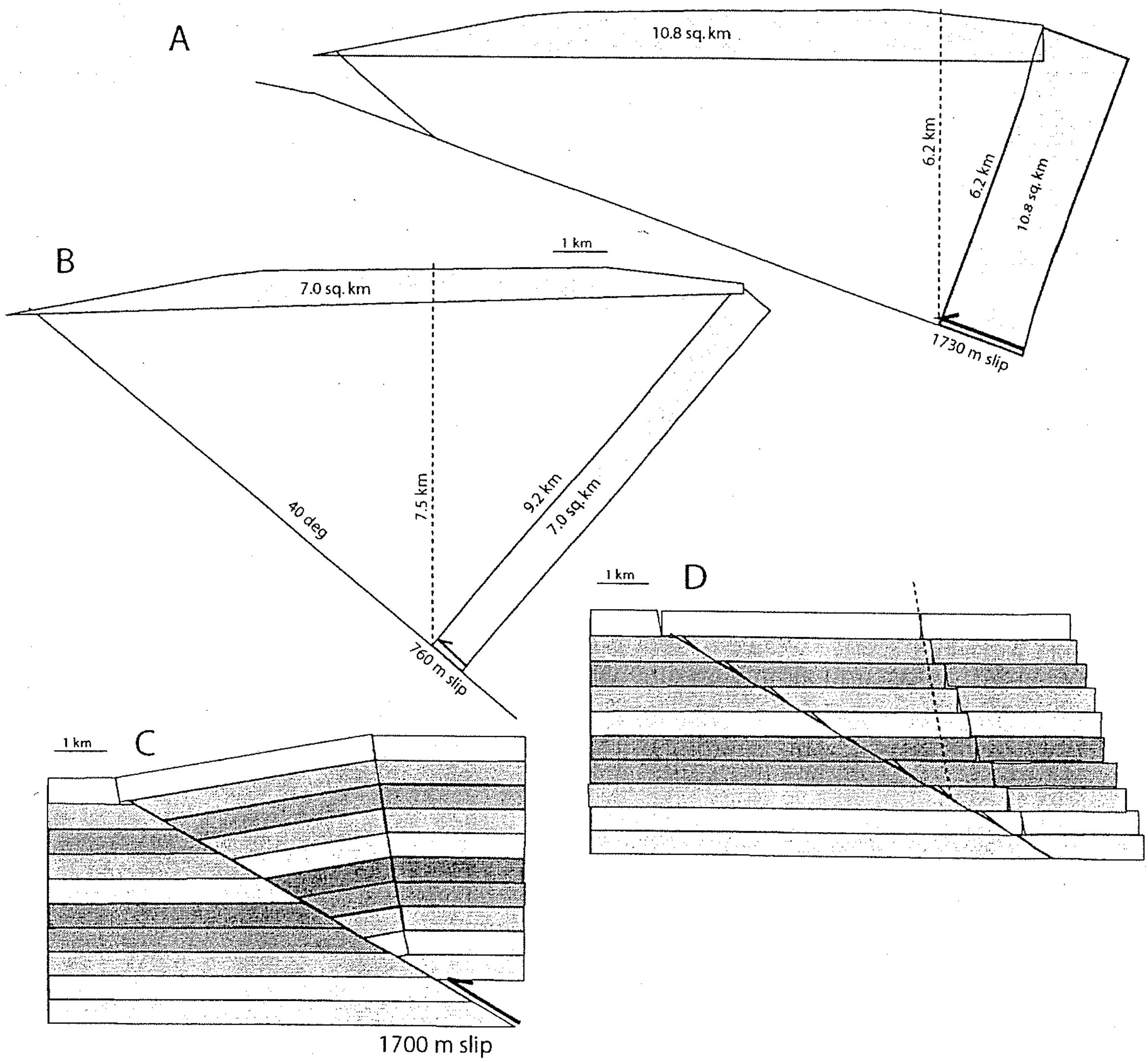


**Figure 11:** A: maximum slip area balance of USGS 44, resulting in an estimate of 1.7 km of slip in the last ~2.5 M.Y. A 20° dip is used for the Shelf Projection blind fault, and the area is based on zero initial dip. B: Minimum slip area balance, resulting in an estimate of 0.8 km of slip. A 40° dip for the San Pedro Escarpment fault is used, and the cross-sectional area of the fold is less because a 2° initial dip is assumed. C: Forelimb model for a fault where slip is gradually converted to folding by horizontal axis rotation of a triangular region. D: Restoration of the model in C, showing that bedding-parallel slip is expected and that the hinge must rotate or migrate through the material. Slip is 1.7 km for a 5 km-wide fold forelimb dipping 10°. This is the same slip estimate as the structural relief divided by the sin of the fault dip. This model is not intended to show the geometry imaged on USGS-44 (Fig. 10), but instead shows that broad, gently-dipping fold limbs can be interpreted as forelimbs, and that forelimbs need not be directly related to backlimbs. The strata are pre-thrust; syn-thrust strata would show progressive tilt and thinning in the hanging-wall.

base of the Compton thrust ramp of Shaw and Suppe (1996). Instead, the fold is interpreted as independent of the modeled kink at the base of the Compton ramp (Shaw and Suppe, 1996), and as being primarily a forelimb caused by slip dying out upwards. We balance the fold area with a sloping rectangle at the point where slip starts to be absorbed in the fold. As with the standard application of area balancing, the rectangle is drawn with its long axis perpendicular to the direction of motion of the hanging-wall with respect to the footwall. Area balancing assumes that material does not move out of the plane of the section. In the case shown here, the right-lateral faults are northeast and southwest of the block being balanced, and do not affect the balance. The fold is long and continuous enough that minor strike-slip motion should not greatly affect the area balance.

An even simpler approach to estimating slip on blind or partially blind faults is to use trigonometry, fault dip, and structural relief, assuming simple block uplift of the hanging-wall. This was done to estimate Holocene slip on the Puente Hills thrust (Dolan et al., 2003). The same approach can be taken here: for a profile that has 0.85 km of structural relief due to slip on a fault dipping 30°, the slip is 1.7 km (**Fig. 11c**).

**Figure 11A** is the maximum slip estimate, where the Shelf Projection blind fault is aligned with the Compton thrust ramp along a 20 deg dip, and it is assumed that there is zero initial dip of the top Repetto. Slip is 1.7 km in this model. **Figure 11B** shows a minimum slip model. The shallow San Pedro escarpment fault dips about 40° near USGS44, but flattens to 30 deg and less at the NW and SE ends of its mapped portion (measured in GOCAD). The 40° dip is shown, and the area of the fold is smaller because an initial dip of 2° is assumed. There is less than 0.8 km of slip in the last 2.5 M.Y. in this model. Both models underestimate slip because volume is lost by sediment compaction and pressure solution. Other variables that are difficult to quantify are the initial dip and age of the top "Repetto". These slip estimates only apply to the part of the fault where the cross section is located.

In **Figures 11C** and **11D**, we show a model for creation of a forelimb by horizontal axis rotation. This model has similarities to the trishear model (Erslev, 1991; Hardy and Ford, 1997, Allmendinger and Shaw, 2000). It is also similar to a model for vertical axis rotations applied to the San Andreas fault system in Salton Trough, California (Armbruster et al., 1998). There, crustal slats of unequal lengths carry different amounts of plate motion for a given amount of rotation. The plate motion accommodated by clockwise rotation is not available for right-lateral motion on the bounding faults. Therefore, slip on the bounding faults is smallest adjacent to the longest rectangular block. Dextral shear is transformed gradually between clockwise rotation and right-lateral slip across triangular regions of rotating blocks bounded by NE-SE left-lateral faults (Armbruster et al. 1998). If **Figure 11C** was a map and not a cross section, left-lateral slip would be dissipated into counterclockwise slip of rectangular blocks separated by right-lateral faults. For **Figure 11C** viewed as a cross section, thrust slip is dissipated into forelimb rotation, with bedding-parallel slip. The fault continues to slip adjacent to the tilting forelimb, rather than folding occurring above the tip of a propagating fault. Many of the faults in the study area are reactivated Miocene normal-separation faults, so that propagation of a new fault need not occur. The model shown has a 5 km-wide limb dipping 10 deg, which is the same as the limb constructed on the top "Repetto" on USGS44 (**Fig. 10B**). Slip is 1.7 km. This is an overestimate if some of the structural relief is due to initial dip. This model is not equivalent to the actual geometry seen on USGS-44 because it does not include the progressive tilting that occurred between 5 and 2.5 Ma, and because a clearly triangular fold limb has not been imaged. As discussed in papers on the Trishear model, propagation of the tip of the blind fault, motion of material through the triangular deformation zone, or curved rather than kinked fold limbs are possible or likely. However, the 1.7 km slip estimate should be accurate because it is the same as structural relief divided by sin(fault dip).

Palos Verdes Peninsula has active surface and rock uplift (LaJoie, 1986). This uplift has been explained as the result of ~3 mm/yr right-lateral slip on the Palos Verdes fault, and a restraining segment (Ward and Valensise, 1994). While the restraining segment supplies a component of convergence, this convergence need not be accommodated solely on the Palos Verdes fault. The width of the fold suggests involvement of a low-angle fault (e.g., Shaw and Suppe, 1996). Ward and Valensise (1994) only explained uplift with respect to sea-level. Based partly on paleo-bathymetry estimates based on paleontology, the increase of structural relief was considered the result of uplift from an initial depth of 850 m (Ward and Valensise, 1994). The Quaternary uplift rate is obtained from elevations of coastal terraces and their inferred ages (Ward and Valensise, 1994). This uplift with respect to sea level underestimates increase in structural relief if Santa Monica and San Pedro basins are subsiding (Bohannon et al., in press; see Pinter et al., 2003)

**Figures 4, 6, and 10** show that the present bathymetric basin lies above the footwall of a zone of NE-dipping faults inferred to have been normal faults during the Miocene. The thin post-Miocene strata above this footwall are consistent with it having been higher-standing than the hanging-wall (includes Palos Verdes Hills). It is expected that growth of the Palos Verdes-Shelf Projection anticlinorium would result in an isostatic response contributing to subsidence of the San Pedro basin. If structural relief is increasing faster than the surface uplift of Palos Verdes Hills, then slip on the San Pedro Escarpment fault or another blind fault is needed to make up the difference.

We have calculated long-term average slip rates of blind faults beneath the Shelf Projection, and now discuss evidence for post-50 ka activity. It is published that folding in this area predates 1 Ma, probably because shallow reflections appear to onlap the fold without being involved in the folding (Nardin and Henyey, 1978). Our reprocessing of USGS data attenuated multiples and images progressively-tilted Pliocene strata on the north limb of the fold (**Fig. 5**). Rapid (.28-.58 mm/yr) Holocene sedimentation shown in cores (Sommerfield and Lee, 2003), and an unconformity imaged at ~300 m below sea floor on certain seismic-reflection profiles, suggests that the non-tilted strata are younger than 0.5 to 1.0 million years, or younger if sedimentation rates have been higher during glacial periods. In addition, lack of northeast limb tilting does not preclude blind fault slip being absorbed in the southwest limb (Fig. 11C). The Miocene strata beneath the Shelf Projection are not deeply eroded, so we cannot call upon rapid rock uplift in this area. However, the wavecut platform cut into Miocene rocks on the Shelf Projection is shallower than eustatic sea level lowstands, suggesting some ongoing rock uplift. If the footwalls of the thrust faults are subsiding, then structural relief is growing faster than rock uplift (Pinter et al., 2003). However, we do not have direct evidence for or against ongoing footwall subsidence in this area.

Post-50 ka strata provide more direct evidence for ongoing deformation. A reflection from the base of ODP site 1015 was correlated to the southwest limb of the anticlinorium (Shipboard Scientific Party, 1997; Piper, et al., 2003). Post-50 ka strata can be followed about 300 vertical meters up the south fold limb on several profiles (**Fig. 10**). Most of this relief is in the hanging-wall of the mapped strand of the San Pedro Escarpment fault zone. Ascribing this relief to folding results in impossibly high estimates of slip. Therefore, these strata must "drape" the fold limb; having been deposited with an initial dip as high as 8°. Turbidity currents can deposit sediment as much as 100 m above the basin floor, with thinning and fining of sediment along the basin margins (ongoing research by W. Normark). An unknown part of the remaining 200 m of relief could be due to active tilting of the southwest limb.

The Palos Verdes-Shelf Projection anticlinorium may have propagated northwest across Santa Monica Canyon. Gardner et al. (2003) show NE-SW cross-sections across the slope north of Santa Monica Canyon. These cross sections show a convex-up seafloor where concave-up might be expected ("convex-up" label in **Fig. 3B**). They ascribe this to a depocenter (Gardner et al. 2003). Two piston cores taken at this seafloor bulge show the strata to be 14,560-15330 and 7910-8130 calibrated years B.P. (Sommerfield et al., 2003). Seismic reflection profiles do not support the depocenter interpretation. However, the few profiles in this area available to us do not clearly show whether or not the Holocene strata are folded or just draped across deeper structure. However, Santa Monica Canyon is more deeply entrenched in the area of this seafloor bulge, suggesting folding (**Fig. 3B**).

The possibility of drape of Holocene and post-50 ka strata has made it very difficult for us to use these strata to provide estimates of rates of ongoing folding. This drape also calls into question slip estimates elsewhere around Los Angeles basin that are based on dips or structural relief of turbidites. Clearly, this is an area for focused sedimentologic study.

## CONCLUSIONS

Digital maps were provided to the SCEC Community Fault Model of several faults. These maps include the offshore Malibu Coast fault, linking faults between the Dume segment of the Santa Monica fault and the Malibu Coast fault, and part of the offshore Santa Monica fault. Structure-contour maps were constructed of the base Pliocene and a ~2.5 Ma horizon. The base of ~50 ka strata was correlated from ODP site 1015 to several faults and folds. The Palos Verdes anticlinorium extends 25+ km west-northwest into Santa Monica Bay, beneath the Shelf Projection. The offshore part includes a progressively-tilting north limb, and a broad south limb. Northeast-dipping blind faults project beneath this structure and close to the Compton thrust ramp. The scale of the active Palos Verdes-Shelf Projection anticlinorium suggests a minimum 800 square km underlying fault-and we have not included possible offshore continuations south of Palos Verdes Hills and an area of convex-up seafloor north of Santa Monica Canyon.

Broad fold limbs have generally been modeled as backlimbs above thrust ramps, or backlimbs above the top of thrust wedges, with the interpreted fault dipping the same direction as the fold limb dip in both cases. Here, we present a model that can explain broad, gently-dipping forelimbs, where the fault dips and limb dip are opposite. This model and area balancing in cross-section were used to estimate slip on blind faults beneath the Shelf Projection. Dip-slip on blind faults beneath this part of the anticlinorium is as much as 1.7 km in the last 2.5 M.Y., or more if sediment compaction and pressure solution are significant. We infer that these blind faults are still active. Although post-50 ka strata are present on the southwest fold limb, we were not able to estimate a rate of folding based on them. That is because thick turbidite flows result in drape of the flanks of the basin. The base of the post-50 ka strata has 40 m of relief across the right-lateral San Pedro Basin fault, part by faulting and the remainder by folding and possibly drape.


## Acknowledgements

Drew Mayerson and others at the U.S. Minerals Management Service provided access to the Digicon data, Tom Wright's and David Okaya's efforts made Exxon data available to SCEC researchers, other industry sources provided additional data. John Armbruster did one set of the earthquake relocations. Egill Hauksson provided a more up-to-date version of the relocated hypocenters referenced as Hauksson (2000). Bruce Luyendyk is supervising Kris Broderick's thesis. Information on petroleum wells along the Los Angeles area coast was found in the repository at Long Beach State operated by Dan Francis. Discussions with Bob Bohannon and Shirley Baher of USGS are appreciated. Eight meter horizontal resolution Multibeam data were provided by P. Dartnell.


**Note:** We have in past abstracts and reports changed the name that we call the Shelf Projection Blind fault. Both the eastern Shelf Projection Blind fault and the San Pedro Escarpment fault may be updip splays of the Compton-Los Alamitos blind thrust. If this relation can be shown with a high degree of confidence, then a single name for all parts of this fault will be less confusing.

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## Reports Published

An unpublished manuscript will be rewritten as two separate papers, one on the Santa Monica-Dume fault and another on the material discussed in this report. The Masters thesis of Kris Broderick, in preparation, will cover material similar to what is in this report; his graduate studies were partially supported by USGS-NEHRP.

Sorlien, C. C., Broderick, K., Kamerling, M. J., Fisher, M., Normark, W., Sliter, R., and Seeber, L, 2003a, Structure and kinematics beneath Santa Monica Bay, California, Pacific Section AAPG abstracts, May 2003, Long Beach

Sorlien, C. C., Broderick, K., Sliter, R., Fisher, M., Normark, W., Seeber, L., and Kamerling, M. J., 2003b, Contributions to the SCEC Community Fault Model: Relating onshore-offshore stratigraphy and fault-fold activity beneath Santa Monica Bay, Annual Report to Southern California Earthquake Center, USC.

Plus two abstracts at SCEC Annual Meeting, September 2003.

Paper supported by previous NEHRP grant.

Pinter, N., Sorlien, C. C., and Scott, A. T., 2003, Fault-related fold growth and isostatic subsidence, California Channel Islands, American Journal of Science, v. 303, p. 300-318

## Data Availability

Well data, including sonic surveys, are public and available from the California Division of Oil and Gas in Long Beach, Dan Francis' data repository at Long Beach, or from us. Wells in Federal waters (more than 5 km from the coast) are usually available from the US Minerals Management Service in Camarillo, but the wells in Santa Monica Bay all predate 1970 and the MMS does not seem to have information on them. The 800x2500 m grids of single channel sparker data, minisparker, and 3.5 kHz data are described in Burdick and Richmond (1982), but are apparently are missing from the sets of microfilm available from the NGDC. The originals can be found with difficulty from the US Minerals Management Service, but it is probably simpler to contact us. A 2.5 km by 2.5 km grid of non-migrated mid-1970s-vintage multichannel seismic reflection data from Digicon has been released by the U.S. Minerals Management Service and the films are in Camarillo. A grid of migrated seismic reflection data from Exxon is available from the Southern California Earthquake Center (contact David Okaya). Other industry seismic reflection data used in this project are not available, but may become available as part of the ongoing effort to transcribe and make public industry data. Our digital structure-contour maps of faults have been provided to the SCEC Community Fault Model (CFM) (http://structure.harvard.edu/cfma/), although some of our faults are not in version CFM-1.01beta. The structure-contour maps of stratigraphic horizons will be made available either through SCEC-CFM or as supplemental data to publications. BASIC programs and awk scripts were written to convert focal mechanism data (e.g., Hauksson, 2000) into our GOCAD format. These are available from C. Sorlien, but are in an old version of Omikron BASIC and would have to be reprogrammed for other languages. Contact Christopher Sorlien at chris@crustal.ucsb.edu for additional information on data.